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13. ABSTRACT (Maximum 200 words)

Key contributions include the following:

- **The adaptation and specialization of multi-channel vibration control techniques based on the characteristic vibration disturbance**

- **Demonstrated the importance of using combinations of multi-channel controller formulations for transient and steady-state vibration disturbance suppression and rejection**

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- Developed a new Hybrid Active Control Formulation which incorporates combination of a Nonlinear-rate feedback scheme and the Filtered-x adaptive feedforward controller for transient and steady-state disturbance suppression and rejection

- Developed a novel model-independent Total Energy Absorption (TEA) active control scheme for active vibration control in structures with vibration response characterized by standing and propagating waveforms.

- Developed a new Dual Active Control Scheme which incorporates a fuzzy adaptive learning rate with the Filtered-x algorithm for separate/combined vibration and acoustic radiation reduction

FINAL REPORT

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7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

K. Craig

Islam A. and Craig, K., "Design, Construction and Testing of a Single-Axis Servomechanism For Control Experiments Involving Coulomb Friction, Backlash and Joint Compliance," Journal of Engineering Design, Vol.5, No.1, 1994.

Islam A. and Craig, K., "Damage Detection and Mitigation of Composite Structures Using Smart Materials," Smart Structures and Intelligent Systems, SPIE Vol. 1917, Smart Structures and Materials, Albuquerque, New Mexico, February 1993.

Islam A. and Craig, K., "Damage Detection in Composite Structures by Using Smart Materials," Journal of Smart Materials and Structures, Vol. 3, 1994, pp. 318-328.

Islam A. and Craig, K., "Active Damage Mitigation in Composite Structures Using Smart Materials," SPIE Conference on Smart Structures and Intelligent Systems, Orlando, Florida, February 1994.

Prakah-Asante, K.O. and Craig, K., "Multi-Channel Control Design for Vibration Minimization of an Active Structure," Recent Development in Stability, Vibration, and Control of Structural Systems, AMD-Vol. 167 ASME, (1993), pp. 35-48.

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Prakah-Asante, K.O. and Craig, K., "Development of an Active Structural Control Method for Vibration and Acoustic Radiation Reduction," SPIE Proceedings, Smart Structures and Intelligent Systems, Vol. 2241 (1995) pp. 305-319.

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J. Wen

S.G. Shu, D.C. Lagoudas, D Hughes, J.T. Wen, ``Modeling of a Flexible Beam Actuated by Shape Memory Alloy Wires," Journal on Smart Materials and Structures, Journal of Smart Materials and Structures, 6, June, 1997, pp. 265-277.

D Hughes, J.T. Wen, ``Preisach Modeling of Piezoceramic and Shape Memory Alloy Hysteresis," Journal on Smart Materials and Structures, Journal of Smart Materials and Structures, 6, June, 1997, pp. 287-300.

D. Hughes, J.T. Wen, ``Passivity Motivated Controller Design for Flexible Structures," AIAA Journal of Guidance, Control, and Dynamics, May-June, 1996, pp.726--729.

P. Akella, X. Chen, W. Cheng, D. Hughes, J.T. Wen, ``Modeling and Control of Smart Structures with Bonded Piezoelectric Sensors and Actuators," Journal on Smart Materials and Structures, 3, pp.344-353, 1994.

P. Akella, J.T. Wen, ``Synthesized Passive Feedback Control of Sensor Rich Smart Structures," 1997 American Control Conference, Albuquerque, NM, June 1997.

C. Dickinson, J.T. Wen, ``Feedback Control with Shape Memory Alloy Wires," 3rd ARO Workshop on Smart Structures, Blacksburg, VA, August 1997.

C.Dickinson, D.C.Hughes, J.T.Wen, ``Feedback Control Using the Shape Memory Alloy Wires," SPIE Conference, San Diego, Feb. 1996.

D. Hughes, J.T. Wen, "Preisach Modeling of Piezoceramic Hysteresis," 4th IEEE Conference on Control Applications, Albany, NY, Sept. 1995.

P. Akella, J.T. Wen, "Synthesized Passive Feedback Control of Sensor-Rich Smart Structures: Experimental Results," 4th IEEE Conference on Control Applications, Albany, NY, Sept. 1995.

C. Dickinson, D. Hughes, J. Wen, ``Hysteresis Modeling and Control in Shape Memory Alloy Actuators," ARO Smart Structure Workshop, Sept., 1995. College Station, MD.

D. Hughes, J. Wen, ``Preisach Modeling and Compensation for Hysteresis in Smart Materials," 1995 SPIE Conference on Smart Structures and Materials, Feb., 1995.

P. Akella, J. Wen, ``Passive Feedback Control of Smart Structures," 1995 SPIE Conference on Smart Structures and Materials, Feb., 1995.

D. Hughes, J.Wen, "Preisach Modeling and Compensation for Smart Material Hysteresis," Society of Eng. Science 31st Annual Meeting: Symposium on Active Materials and Smart Structures, Oct., 1994.

P. Akella, X. Chen, D. Hughes, J. Wen, "Modeling and Control of Smart Structures with Surface Bonded Piezoelectric Sensors and Actuators: A Passivity Perspective," 1994 SPIE Conference on Smart Structures and Materials, Feb., 1994.

D. Hughes, J. Wen, "Passivity Motivated Controller Design for Flexible Structures," 1993 IEEE International Conference on Robotics and Automation, May, 1993, pp.749--754.

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P. Akella, X. Chen, J. Wen, "Application of Passivity Motivated Controller Design for a Nonlinear Flexible Pointing System," 1993 American Control Conference, June, 1993, pp.1617--1621.

H. Tiersten

"Electroelastic Equations for Electroded Thin Plates Subject to Large Driving Voltages," H.F. Tiersten, Journal of Applied Physics, 74, 3389-3393 (1993).

"Equations for the Extension and Flexure of Relatively Thin Electroelastic Plates Undergoing Large Electric Fields," H.F. Tiersten, Mechanics of Electromagnetic Materials and Structures, "AMD-Vol. 161, Book No. G00784-1993, The American Society of Mechanical Engineers, pages 21-34.

"An Elastic Analysis of Laminated Composite Plates in Cylindrical Bending Due to Piezoelectric Actuators," Y.S. Zhou and H.F. Tiersten, Journal of Smart Materials and Structures, 3, 255-265 (1994).

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"On the Influence of Material Objectivity on Electroelastic Dissipation in Polarized Ferroelectric Ceramics," H.F. Tiersten, Mathematics and Mechanics of Solids, 1, 45-55 (1996).

"Elastic Analysis of the Transfer of Shearing Stress from Partially Electroded Piezoelectric Actuators to Composite Plates in Cylindrical Bending," J.S. Yang and H.F. Tiersten, Journal of Smart Materials and Structures, 6, 333-340 (1997).

"Electroelastic Equation's Describing Slow Hysteresis in Polarized Ferroelectric Ceramic Plates," L. Huang and H.F. Tiersten, to be published in the Journal of Applied Physics.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

K. Craig

Abu Islam, Ph.D., Mechanical Engineering, December 1994
K.O. Prakah-Asante, Ph.D., Mechanical Engineering, May 1995
Andrew Wright, Ph.D., Mechanical Engineering, August 1996
James Fairweather, Ph.D., Mechanical Engineering,

J. Wen

Declan Hughes, Ph.D. student, completed in 2/97
Padma Akella, Ph.D. student, completed in 10/97
Carrie Dickinson, Ph.D. student, completed in 11/97

H. Tiersten

Yan Sheng Zhou - Post Doctoral Research Associate
Ben Je Lwo - Research Assistant
Jia Shi Yang - Post Doctoral Research Associate
Lidu Huang - Research Assistant, Ph.D. 1997

9. REPORT OF INVENTIONS

Carl, A., Chen, M., Craig, K., Fairweather, J, Hirsch, R., Wright, A., 1996, United States Patent 5575790, “Shape memory alloy internal linear actuator for use in orthopedic correction”.

10. BRIEF OUTLINE OF RESEARCH FINDINGS

K. Craig

1. Islam and Craig

    - A model of piezoceramic materials embedded in composites has been developed that is detailed enough to capture the essential dynamic response of the structure and also simple so that it can be used for on-line control applications.

    - Measurement of dynamic characteristics of a structure is potentially a very attractive method of non-destructive testing, since the properties can be measured at one point of the structure and are independent of position chosen.

    - The use of active materials for system identification has been found advantageous since the condition of the structure can be continuously monitored and by using an on-board microprocessor, the sensor output can be continuously evaluated.

    - It has been found that the presence of damage can be detected simply by noting the changes in natural frequencies of the structure. Location and assessment of damage severity requires that a neural network be trained with dynamic responses from a model of the structure having damage in different locations and various sizes.

    - For closely spaced input frequencies of the neural network, the uses of fuzzification greatly improved the convergence and accuracy of the network.

    - It is possible to use this approach to monitor the growth of damage by using a damaged state as a baseline for measurement.

    - Mitigation of damage by reduction of dynamic moments at the damage locations has been proved feasible provided the actuators have enough control authority.

2. Prakah-Asante and Craig

    - The objective of this research was the development of new and improved active control methods for vibration and acoustic radiation minimization in structures using piezoelectric materials as sensors and actuators. Disturbance minimization of over 20 dB were achieved from real-time experimental implementation of active control methods developed.

    - Key contributions include the following:

        - The adaptation and specialization of multi-channel vibration control techniques based on the characteristic vibration disturbance

- Demonstrated the importance of using combinations of multi-channel controller formulations for transient and steady-state vibration disturbance suppression and rejection

- Developed a new Hybrid Active Control Formulation which incorporates combination of a Nonlinear-rate feedback scheme and the Filtered-x adaptive feedforward controller for transient and steady-state disturbance suppression and rejection

- Developed a novel model-independent Total Energy Absorption (TEA) active control scheme for active vibration control in structures with vibration response characterized by standing and propagating waveforms.

- Developed a new Dual Active Control Scheme which incorporates a fuzzy adaptive learning rate with the Filtered-x algorithm for separate/combined vibration and acoustic radiation reduction

3. Wright and Craig

- Discovered that convergence of LMS System Identification Algorithm in Active Sound Cancellation depends on the coherence between the test signal broadcast from the actuator and the error microphone. This coherence is degraded for low level test signals. However, when the power in the test signal exceeds the noise threshold, convergence is assured. Further increase in power results in no improvement and indeed degrades performance when echoes begin to interfere with the direct path.

- Formed some preliminary results regarding the time domain cepstral transform (TDCT) for dereverberating acoustic signals. This is intended to help the coherence described above for large test signals. Discovered that time delays can be found from the number of zero eigenvalues in the TDCT matrix.

- Developed a compact acoustic actuator using piezoelectric patches to excite resonances in a plate. This actuator was used to cancel sound. Its main drawback is that its response below 400 Hz was minimal, which is the primary area where ASC is needed. Further work needs to be invested in lowering the effective frequency response. Modeling and simulation to try out preliminary concepts should be pursued.

4. Fairweather and Craig

- Modeling approaches to the induced-strain actuation of structural systems presently lack methods of satisfactorily dealing with structures possessing complex boundaries, material anisotropy, and point mass loading. In addition, the most frequently employed models of induced-strain actuation, static equivalent-force models, have been shown in experimental studies to be poor predictors of both system resonant frequencies and the stress field in the induced-strain actuator.

- A modeling approach based on the mechanical impedance of the host structure has been shown in the literature to accurately predict the measured dynamic behavior of several simple dynamic systems driven by induced-strain actuators. This research extends this impedance approach to more complex structures.

- The present work centers on the use of the eigenvectors and eigenvalues extracted from finite-element-based normal-mode analysis to determine the mechanical impedance of the host structure. Such an approach extends the applicability of present impedance models to structures for which closed-form expressions of mechanical impedance do not exist.

- Equations are developed to compute the mechanical impedance of the structure based on the finite element results. These impedances are employed to obtain the dynamic response of the previously studied cantilever beam and simply-supported plate structure. Comparisons of the predicted response are made with models published in the literature, including models incorporating analytically determined impedances. The predictions of the present approach demonstrate excellent agreement with the prior analytical impedance models.

- Experiments are conducted for the purpose of beam model validation. Prior static equivalent-force models are shown incorrectly predict the first resonance of the driven beam system by nearly 20%, while the FEA-based impedance model is shown to be accurate to within 2.5%.

- The FEA-based impedance model of the plate system is compared to experimental results published in the literature, and the new approach demonstrates excellent predictions of the system dynamic response when compared to the previous static equivalent-force approach.

- The methods developed can be directly extended to complex structures, and a research plan centered on experimental verification of the approach is proposed to further the present work.

J. Wen

- Preisach model for hysteresis:
  We have applied the Preisach model for the hysteresis found in piezoelectric materials and shape memory alloys. We have demonstrated experimentally that this physically motivated phenomenological model applies well to piezoceramic materials and adequately to SMA. The Preisach model is amenable to efficient identification as well as to direct inversion. We have demonstrated output following through direct cancellation of the hysteretic effect in both PZT and SMA.

- Passivity based control:

We have shown that PZT voltage and collocated strain rate form a passive pair which can be used for robust closed loop feedback control. However, under sample-and-hold implementation, the strain rate measurement and high bandwidth of the PZT device causes a large artificial noise. We have extended the passive feedback scheme to include collocated strain feedback (which is not passive with respect to the voltage input) and other noncollocated sensor feedback. A linear matrix inequality approach is used to synthesize an "optimal" passive output based on the available sensors which can be in turn used in existing passive feedback strategies.

- Near and Far Effects:
  We have successfully explained the so-called "Near and Far Effect" observed in piezoceramics. Basically, existing models predict well the transfer function from PZT to strain gauge when they are far apart, but poorly when they are very close. We use a input-dependent modal expansion to better approximate the solution of the governing partial differential equation.

- Feedback Control of SMA:
  We have demonstrated that the dynamic effect in shape memory is not negligible especially when it is connected with a flexible host structure. Based on a simplified model that we have developed (Shu, Lagoudas, and Wen), we can prove closed loop stability for SMA force control when SMA is connected with a rigid surface, and predict (and have experimentally observed) instability when SMA is connected to a flexible beam. We have developed both fixed gain and adaptive control schemes that can achieve closed loop stability by using the beam strain feedback. In the case of adaptive control, steady state error can be removed with no model information required. It is also observed that sampling significantly affects the amplitude of the steady state oscillation.

H. Tiersten

- Non-dissipative electroelastic equations for fully electroded actuators subject to large electric fields were obtained from existing general recoverable nonlinear, rotationally invariant, electroelastic equations. The equations, which contain only one component of electric field, are for fully electroded actuators only. The equations for the thin stress-free polarized ferroelectric ceramic plate subject to large electric fields were shown to account for existing experimental data for the case of positive increments in electric field only.

- On account of the restrictions mentioned for actuators, two-dimensional non-dissipative electroelastic plate equations for both unelectroded and electroded portions of actuators were derived. These equations are linear in the deformation and nonlinear in the electric fields. The equations hold for thicker actuators because flexure was included in the description as well as extension.

- Laminated composite plates forced into cylindrical bending by fully electroded actuators were treated using both approximate plate equations and those of linear elasticity. The

results obtained from the two approaches were compared and it was shown that for large span length-to-thickness ratios the agreement is quite good but for small ones it is not good at all. In addition, the plate solution indicates that the shearing force between the actuator and the composite plate is transferred as a delta function at the edge of the actuator, while the linear elastic solution shows that the actual distribution is transferred near the edge and becomes singular at the edge.

- Non-dissipative two-dimensional equations describing the flexure of symmetric laminated composite plates with partially electroded actuators attached were derived and applied to the problem of the cylindrical bending of the plate due to voltages applied to the actuators. The plate solution revealed that even when the electrodes end a very short distance from the edge of the actuators, the shearing stress transferred is non-singular.

- Since the approximate plate equations tend to be inaccurate for the calculation of the transfer of horizontal shearing stress in the case of cylindrical flexure discussed in the preceding paragraph, a linear elastic analysis of that problem was performed. The calculations performed using the accurate linear elastic analysis revealed that the maximum shearing stress is less than 1/10 of that obtained from the plate equations and extends over a distance 10 times as large. This distance, however, is still quite small so that the edges of the electrodes can be quite close to the edge of the actuator and still have the shearing stress small at the edge.

- Existing rotationally invariant electroelastic equations were extended to include the simplest mechanical and electrical viscous type dissipation. The nonlinear description obtained satisfies the principle of material objectivity. In the absence of thermal considerations the description reduces to seven equations in seven dependent variables. In the linear version for the polarized ferroelectric ceramic, the electrical dissipative variable contains the spin tensor because of the residual polarization. If the electric field is used as the independent thermodynamic variable instead of the polarization, which was used, the resulting objective description reduces to four equations in four dependent variables. In the linear limit for the polarized ferroelectric ceramic the electric variable does not contain the spin tensor because there is no biasing electric field. In the application to actuators both systems reduce further because of the condition of plane stress.

- It has been shown that for thin wide beams forced by actuators on the surfaces, the expression commonly used for the applied moment should be reduced by the factor $(1-\nu)$, where ν is the planar Poisson's ratio for the plate. This is directly analogous to the reduction of the plate elastic constant to the beam elastic constant and arises for the same reason.

- The rotationally invariant equations of recoverable nonlinear electroelasticity have been extended to account for irreversible slow hysteresis effects, which occur when polarized ferroelectric ceramics are driven by large electric fields. The extension is accomplished by the use of internal variables so that the description is consistent with thermodynamics. All material irreversibility. is taken to be a consequence of the polarization electric field

irreversibility. Since the residual polarization is in the fixed thickness direction, only one internal variable was required. Since we were concerned with the slowest possible hysteresis, we ignored the resulting evolution equation and took the known irreversible thickness polarization-electric field saturation curve as the starting curve. Since the residual polarization at zero electric field is always the starting point, the description was readily extended from the saturation loop to narrower major hystersis loops by means of reasoning motivated by domain switching. After the general nonlinear three-dimensional equations were obtained, they were reduced to linear strain and plane-stress because all experimental data available was from strain measurements on a thin wide beam forced by voltages applied to very thin polarized ferroelectric ceramic actuators on the surfaces. On account of this the equation for the thin wide beam with irreversible actuators attached was derived. The resulting equation was used in the calculations for comparison with experiment. The new irreversible material coefficients were obtained from data on one major hysteresis loop along with the coefficients in the saturation polarization - electric field relation. These then known coefficients were used to calculate other hysteresis loops, which were shown to agree quite well with measurements. It was also shown that proper control of the time at which the driving voltage was switched off could significantly increase the lifetime of an actuator by reducing the amount of depoling in an operation.

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Final Report

Sumbitted by

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A. Research Accomplishments

A generic form of Gibbs free energy for polycrystalline Shape Memory Alloys (SMAs) has been developed, by forming the increments of both elastic potential energy and Gibbs chemical energy over a Representative Volume Element (RVE) with respect to an infinitesimal increment of martensite. The initial material heterogeneity of SMAs, which is essential for the initiation of the phase transformation, was modeled by connecting the reference Gibbs energy with a probability distribution function. In Part I of a three-part paper, the theoretical derivations are presented. Specific cases of the thermomechanical response of SMAs predicted by the model are presented in Part II, together with experimental results for phase transformation at constant plastic strains. Experimental results and model predictions for cyclic loading of SMAs with evolving plastic strains are considered in Part III of a trilogy on SMAs.

A series of experiments performed on NiTi SMA wires undergoing thermally induced cyclic phase transformation under constant applied load was utilized for model simulations and subsequent comparisons with model predictions. Using the present model, thermally induced phase transformations under varying magnitude of applied load can be modeled for both untrained and trained SMAs. Finally, an application of the model to stress induced phase transformation in thin SMA specimens, where transformation strain localization occurs, has been explored. Part III of this trilogy on SMAs studies the evolution of plastic strains accumulating in thermally induced cyclic phase transformation under constant applied load, therefore fully characterizing the thermomechanical response of SMAs under undergoing multiple operating cycles.

Experimental results of the cyclic thermally induced phase transformation under constant applied load have been investigated. It has been observed that the accumulation of plastic strains continues beyond a large number of cycles (2,000), while TWSM is saturated and remains stable after 100 to 300 transformation cycles, depending on the magnitude of the applied load. Motivated by the experimental observations, and based on the general framework established in the first two parts of this series of three papers on SMAs (Bo and Lagoudas, 1997, Lagoudas and

Bo, 1997), evolution equations for the accumulation of plastic strains and plasticity related back and drag stresses, which govern the evolution of TWSM, have been proposed. Finally, model predictions are compared with experimental data, and a procedure for the determination of material constants has been described. Combined with the formulation developed in Parts I and II, the cyclic thermomechanical response of SMAs can be fully characterized using the proposed model.

A connection between the Preisach hysteresis model and the above thermomechanical model has also been investigated. The memory (wiping out) property for the present model is determined in a way similar to that of the Preisach model. Comparisons between the present model predictions and the experimental results show that the present model accurately predicts the minor loop hysteresis response of SMAs, even when such minor loops are close to the transformation start and finish points. Compared with the Preisach model, the present hysteresis model follows a thermodynamic formulation, which makes it easier to account for the effects of changing loading paths and two-way memory effect induced by cyclic loading. The developed numerical implementation algorithm can also be incorporated easily in conjunction with other existing thermomechanical constitutive models, thus providing a general scheme for the modeling of hysteretic response of SMAs, based on physical parameters.

Finally, an adaptive control methodology for identification and compensation for a class of hysteresis models employed for the representation of active materials has been implemented. A theoretical framework has been derived that establishes the well-poseddness of a nonlinear identification formulation for characterizing a class of static hysteresis phenomena in a class of actuators associated with smart materials, where conditions have been derived that guarantee the convergence of Galerkin approximations for the Krasnosel'skii-Pokrovskii (KP) integral hysteresis operator. A linearly parametrized form of the KP integral operator, suitable for gradient adaptive control, that provides numerical examples of adaptive identification from a constitutive law that characterizes a class of SMA actuators undergoing thermomechanical actuating paths, has been derived and implemented.

B. Highlights of Key Research Accomplishments

1. Devised a constitutive model for cyclic loading of SMA actuators and used it for shape control of active trailing edge flaps.
2. Devised a training procedure for SMA actuators and used it to condition actuators for active composites.
3. Implemented an Active Flap Deployment System for BVI control.
4. Developed a shape and tracking control algorithm for an active beam with SMA actuators using nonlinear hysteretic control algorithms.
5. Designed and tested an active elastomeric composite damper with SMA particles.
6. Developed the theory of Active Flexible Rods with embedded SMA actuators.
7. Established a connection between Preisach hysteresis models used for control with micromechanics based models of polycrystalline SMA.
8. Demonstrated the connection between themal, mechanical and structural coupling in active structures with SMA actuators.
9. Modeled the behavior of hybrid active plates composed of piezoelectric and SMA layers.

10. Implemented using layerwise FEM the structural response of active composite laminates with SMA layers.

C. Examples of technology transfer

1. The main interaction with industry that we had on SMA was Bell Helicopter (Warren Young), which independently funded a project on elastomeric damper stabilization by utilizing SMA particles.
2. We have (Texas A&M U.) a CRDA with the Army Vehicle Structures Directorate at Langley (Kevin O'Brien). We plan periodic visits to Langley to exchange technical information.
3. We have (Texas A&M U.) a CRDA with the Naval Air Warfare Center (David Barrett). We used this CRDA to have access to SMA particles that we embedded in elastomeric dampers for the Bell Helicopter project.
4. We started working with the Naval Surface Warfare Center in Annapolis (we are currently negotiating a project to be initiated in the summer of 97), where we will use our established technology on active flaps with SMA actuators developed under ARO funding, to study the similar problem for a hydrofoil. The Navy will give us seed funding to carry out an initial feasibility study with Othon Rediniotis, and we hope to make progress in that area within the next year with the support of David Winyard.
5. We are currently working with Othon on a STTR (phase I), funded by ONR, where we are trying to implement some of the ideas of SMA actuated flexible structures for underwater vehicles and mimic the motion of biological systems.
6. There is extensive cooperation with Martin Marietta (Bernie Carpenter). We are planning to use data from the active flap they built for the smart wing program to validate our own simulations, both on modeling the actuation and the control strategies implemented.
7. Recently there is an exchange of technical information and genuine interest from Northrop Grumman (Peter Jardine). Northrop Grumman is interested in our SMA FEM model to be used in the design of the torque tube actuators, which will be used in the second phase of the smart wing project.
8. Our main materials supplier and supporter with technical information and data all these years is Dr. M. Schetky from Memry Corporation. He is providing us with SMA torque tube actuators, to be tested in our facilities. In return we share data and our findings under the ARO program.
9. Boeing has also expressed an interest in our SMA model and we have provided copies of our papers and our Fortran code to them (Dean Jacot).
10. There is a technical exchange with laboratires abroad, especially France and Russia. With the ARO European office fundind the proposal of Prof. Volkov, this cooperation will reach a point where we could have joint students and publish jointly papers. In addition, I have evaluated and recently asked to monitor a large project on SMA coupling devices funded by congress in Russia, to redirect Russian scientists from military to civilian research (International Science and Technology Center- (ISTC) project N 294). I hope that we can influence the Russian scientists to start research activities relevant to US interests.

Our numerical implementation of Shape Memory Alloy actuators is being used by NRL in the design of the second phase smart wing for Northrop Grumman. According to Virginia DeGiorgi from NRL, who is working on the design of the smart wing, our numerical

implementation is currently the only one available capable of 3-D computations, which are necessary for the torque tube actuators used in the smart wing. The development of this sofeware was supported by the ARO URI on smart materials at RPI/Texas A&M, as a result of several years of basic research on the model development and then the implementation phase.

2. Mostly due to my publication record on work funded by ARO during the past five years, I have recently been selected as one of 15 young scientists from a nationwide search by the institute for defense analyses (ida). The institute seeks nominations mainly from universities and every two years forms a group of 15 promising scientists below the age of 40 from all disciplines (engineering and sciences). I was honored to be selected this year to serve in this panel for the next two years and visit the different DOD facilities, Pentagon, State Department and other strategic agencies related to DOD. The objective of this panel is to make aware the participating scientists of trends in the new technologies vital for the security of the country.

D. HONORS AND AWARDS

Who's Who in America, 1995-
Who's Who in Science and Engineering, 1996-
Adaptive Structures and Material Systems Best Paper Award, presented by The American Society of Mechanical Engineers, 1995.
TEES Research Fellow, 1995, 1996.
TEES Senior Research Fellow, 1997.
Defense Science Study Group, Institute for Defense Analyses, 1998-1999.

E. Student Thesis Supervision

UNDERGRADUATE (the following list includes only students who wrote a research report; a much larger number of undergraduate students have participated in the research project over the years as workstudents or student technicians)

1. Matthew E. Rosenthal, "Self Biased Actively Cooled Shape Memory Alloy Apparatus," AERO 485-305 project, Summer 1993.
2. Brett J. deBlonk, "Design of Flexible Rods with Embedded Shape Memory Alloy Actuators, NSF supported TEES Undergraduate Summer Research Program, Summer 1993.
3. Wendell S. Bielefeld, "Potential Active Cooling Methods for Increasing the Cycle Rate of Shape Memory Alloy Wires," AERO 485-305 project, Fall 1993.

Robert Worsham, "Characterization of SMA-Elastomeric Composite Dampers," TEES Undergraduate Summer Research Fellow, Summer 1995.

Luke Garner, "Numerical Simulation of Thermomechanical Response of a Thermoelectric Shape Memory Alloy Actuator," TEES Undergraduate Summer Research Fellow, Summer 1996.

MASTERS

Graduated:

1. Jamie Pfaeffle, "Active Flexible Rods with Embedded Shape Memory Alloy Actuators: Theory, Design and Experiments," 9/91-5/93.
2. Stephen D. Howard, "The Thermomechanical Constitutive Experimentation of Ni-Ti Shape Memory Alloy Strips and Rods," 8/93-8/95.
3. Abu Bakar Siddiq Qidwai, "Numerical Evaluation of the Constitutive Response of Shape Memory Alloys," 9/93-12/95

Brett J. deBlonk, "Fabrication and Evaluation of SMA-Silicon Rubber Continuous-Fiber and Particulate Composites," 1/94-8/95.

Matthew D. McNeese, "Fabrication of NiTi Shape Memory Alloy From Elemental Powders by Hot Isostatic Prressing," 7/94-12/97.

DOCTORAL

Graduated:

Zhonghe Bo, "Constitutive Response of Shape Memory Alloys and Composites," 8/92-8/96.

Gongming Xu, "Shape Control of Active Composites," 3/94-12/96 (co-chair).

Glenn Viktor Webb, "Adaptive Identification and Compensation for a Class of Hysteresis Operators," 5/95-5/98 (co-chair).

Current:

David Miller, "Fabrication and Mechanical Characterization of Active Composites," 6/96-.

Abu Bakar Siddiq Qidwai, "Finite Deformations in Shape Memory Alloys," 1/96-

POSTDOCTORAL

1. James G. Boyd, "Thermodynamic Formulation of the Constitutive Response of Shape Memory Alloys," 8/92-6/94.
2. Abhijit Bhattacharyya, "Fast Thermoelectric Cooling of SMA," 3/94-12/96.
3. Declan Hughes, (jointly with Dr. Junkins) "Design of Mechanical and Control Experiments in Active Materials and Smart Structures," 1/96-12/96.

Zhonghe Bo, "Thermomechanical Modelling of the Cyclic Response of SMA's," 9/96-present.

F. Publications

Refereed Journal Publications

1. LAGOUDAS, D.C., and TADJBAKHSH, J.G., 1992, "Active Flexible Rods with Embedded SMA Fibers," Smart Materials and Structures 1, pp. 162-167.

LAGOUDAS, D.C., and TADJBAKHSH, I.G., 1993, "Deformations of Active Flexible Rods with Embedded Line Actuators," Smart Materials and Structures 2, pp. 71-81.

TADJBAKHSH, I.G., and LAGOUDAS, D.C., 1994, "Variational Theory of Motion of Curved, Twisted and Extensible Elastic Rods, International Journal of Engineering Science 32 No. 4, pp. 569-577.

BOYD, J.G., and LAGOUDAS, D.C., 1994, "Thermomechanical Response of Shape Memory Composites," Journal of Intelligent Material Systems and Structures 5, pp. 333-345.

LAGOUDAS, D.C., BOYD, J.G., and BO, Z., 1994, "Micromechanics of Active Composites with SMA Fibers," ASME Journal of Engineering Mechanics and Technology 116, pp. 337-347.

LAGOUDAS, D.C., and BO, Z., 1994, "The Cylindrical Bending of Composite Plates with Piezoelectric and SMA Layers," Journal of Smart Materials and Structures 3, pp. 309-317.

LAGOUDAS, D.C., and DING, Z., 1995, "Modeling of Thermoelectric Heat Transfer in Shape Memory Alloy Actuators: Transient and Multiple Cycle Solutions," International Journal of Engineering Science 33, pp. 2345-2364.

BOYD, J.G., and LAGOUDAS, D.C., 1996, "A Thermodynamical Constitutive Model for Shape Memory Materials. Part I. The Monolithic Shape Memory Alloy," International Journal of Plasticity 12, No. 6, pp. 805-842.

BOYD, J.G., and LAGOUDAS, D.C., 1996, "A Thermodynamical Constitutive Model for Shape Memory Materials. Part II. The SMA Composite Material," International Journal of Plasticity 12, No. 6, 843-873.

LAGOUDAS, D.C., BO, Z., and QIDWAI, M.A., 1996, “A Unified Thermodynamic Constitutive Model for SMA and Finite Element Analysis of Active Metal Matrix Composites,” Mechanics of Composite Materials and Structures 4, pp. 153-179.

BHATTACHARYYA, A., and LAGOUDAS, D.C., 1997, “A Stochastic Thermodynamic Model for the Gradual Thermal Transformation of SMA Polycrystals,” Journal of Smart Materials and Structures 6, No.3., pp. 235-250.

XU, G.-M., LAGOUDAS, D.C., HUGHES, D., and WEN, J.T., 1997, “Modeling of a Flexible Beam Actuated by Shape Memory Alloys Wires,” Journal of Smart Materials and Structures 6, No.3., pp. 265-277.

LAGOUDAS, D.C., MOORTHY, D., QIDWAI, M.A., and REDDY, J.N., 1997, "Modeling of the Thermomechanical Response of Active Composite Laminates with SMA Layers," Journal of Intelligent Material Systems and Structures 8, pp. 476-488.

LAGOUDAS, D.C., and BHATTACHARYYA, A., 1997, "On the Correspondence Between Micromechanical Models for Shape Memory Alloys and the Preisach Model for Hysteresis," Mathematics and Mechanics of Solids 2, pp. 405-440.

Accepted Journal Publications

BHATTACHARYYA, A., and LAGOUDAS, D.C., 1997, "Modeling of Thin Layer Extensional Thermomechanical SMA Actuators, " International Journal of Solids and Structures.

LAGOUDAS, D.C. and SHU, S.G., 1997, "Residual Deformation of Active Structures with Shape Memory Alloy Actuators," International Journal of Mechanical Sciences.

De BLONK, B.J. and LAGOUDAS, D.C., 1997, "Actuation of Elastomeric Rods with Embedded Two-Way Shape Memory Alloy Actuators," Journal of Smart Materials and Structures.

JONNALAGADA, K.D., SOTTOS, N.R., QIDWAI, M.A., and LAGOUDAS, D.C., 1998, "Transformation of Embedded Shape Memory Alloy Ribbons," Journal of Smart Materials and Structures.

BO, Z. and LAGOUDAS, D.C., 1997, "Thermomechanical Modeling of Polycrystalline SMAs Under Cyclic Loading, Part I: Theoretical Derivations," International Journal of Engineering Science.

LAGOUDAS, D.C. and BO, Z., 1997, "Thermomechanical Modeling of Polycrystalline SMAs Under Cyclic Loading, Part II: Material Characterization and Experimental Results for a Specific Transformation Cycle," International Journal of Engineering Science.

BO, Z. and LAGOUDAS, D.C., 1997, "Thermomechanical Modeling of Polycrystalline SMAs under Cyclic Loading, Part III: Evolution of Plastic Strains and Two-Way Shape Memory Effect, International Journal of Engineering Science.

Submitted Journal Publications

BO, Z. and LAGOUDAS, D.C., 1997, "Thermomechanical Modeling of Polycrystalline SMAs under Cyclic Loading, Part IV: Modeling of Minor Hysteresis Loops," International Journal of Engineering Science.

WEBB, G., KURDILA, A., LAGOUDAS, D.C., and BO, Z., "Identification and Adaptive Control for a Class of Hysteresis Operators," AIAA Journal of Guidance and Control.

WEBB, G., BO, Z., KURDILA, A., and LAGOUDAS, D.C., "Adaptive Identification of a Parameterized Integral Hysteresis Operator Using a Gradient Adaptive Law," Journal of Intelligent Material Systems and Structures.

Books

Chapter Contribution

LAGOUDAS, D.C., BO, Z., BOYD, J.G. and QIDWAI, M.A., 1997, "Thermomechanical Modeling of Shape Memory Alloys and Composites," in Active Structures, Devices, and Systems – Structronic Systems, Editors, H.S. Tzou, G.L. Anderson, and M.C. Natori, World Science Publishing Company, Vol. 1, pp. 197-246.

Editor

1. ANDERSON, G. and LAGOUDAS, D.C., Editors, 1994, Active Materials and Smart Structures, Proc. SPIE-Vol. 2427, SPIE, Bellingham, Washington.

Papers in Proceedings Volumes and Edited Books

1. LAGOUDAS, D.C., and TADJBAKHSH, I.G., 1991, "Active Flexible Rods with Embedded SMA Fibers," Proceedings of ADPA/AIAA/ASME/SPIE Conference on Active Materials and Adaptive Structures, November 4-8, 1991, Alexandria VA, IOP Publishing Ltd., Bristol, England, pp. 911-916.

2. TADJBAKHSH, I.G., and LAGOUDAS, D.C., 1992, "Variational Theory of Dynamic Deformations of the Curved and Twisted Elastica," Proceedings of the Tenth Army Conference on Applied Mathematics and Computing, 16-19 June 1992, West Point NY.

3. LAGOUDAS, D.C., and TADJBAKHSH, I.G., 1993, "Deformations of Active Flexible Rods with Embedded Line Actuators," Recent Development in Stability, Vibration, and Control of Structural Systems, AMD-Vol. 167, A. Guran, ed., American Society of Mechanical Engineers, New York, pp. 89-106.

4. LAGOUDAS, D.C., and BO, Z., 1993, "Stress Induced Phase Transformations in Piezoelectric Laminates with Shape Memory Alloy Layers," Recent Development in Stability, Vibration, and Control of Structural Systems, AMD-Vol. 167, A. Guran, ed., American Society of Mechanical Engineers, New York, pp. 107-118.

5. BOYD, J.G., and LAGOUDAS, D.C., 1993, "A Thermodynamically Based Constitutive Model for the SME due to Transformation and Reorientation," Proceedings of 4th International Symposium on Plasticity and its Current Applications, Baltimore MD, 19-23 July 1993.

6. PFAEFFLE, H.J., LAGOUDAS, D.C., TADJBAKHSH, and CRAIG, K.C., 1993, "Design of Flexible Rods with Embedded SMA Actuators," in Smart Structures and Materials 1993: Smart Structures and Intelligent Systems, N. W. Hagood, and G.J. Knowles, eds., Proc. SPIE 1917, pp. 762-773.

7. BOYD, J.G., and LAGOUDAS, D.C., 1993, "Thermomechanical Response of Shape Memory Composites," in Smart Structures and Materials 1993: Smart Structures and Intelligent Systems, N. W. Hagood, and G.J. Knowles, eds., Proc. SPIE 1917, pp. 774-790.

8. PFAEFFLE, H.J., CRAIG, K.C., and LAGOUDAS, D.C., 1993, "Active Flexible Thick Cylinders with Embedded Shape Memory Alloy Actuators," Presentation Materials from the First Workshop on Smart Structures, University of Texas at Arlington, 22-24 September 1993, 8 pages, (no page numbers in volume).

9. BOYD, J.G., and LAGOUDAS, D.C., 1993, "A Micro-thermodynamics Analysis of Shape Memory Alloy Composites," Presentation Materials from the First Workshop on Smart Structures, University of Texas at Arlington, 22-24 September 1993, 14 pages, (no page numbers in volume).

10. LAGOUDAS, D.C., and BO, Z., 1993, "Active Hybrid Composite Laminates with Piezoelectric and Shape Memory Alloy Layers," Presentation Materials from the First Workshop on Smart Structures, University of Texas at Arlington, 22-24 September 1993, 10 pages, (no page numbers in volume).

11. BOYD, J.G., and LAGOUDAS, D.C., 1994, "A Thermodynamical Constitutive Model for the Shape Memory Effect Due to Transformation and Reorientation," in Smart Structures and Materials 1994: Smart Materials, V.K. Varadan, ed., Proc. SPIE 2189, SPIE—The International Society for Optical Engineering, Bellingham, Washington, pp. 276-288.

12. BO, Z., and LAGOUDAS, D.C., 1994, "Deformations and Thermal Response of Active Flexible Rods with Embedded SMA Actuators," in Smart Structures and Materials 1994: Smart Structures and Intelligent Systems, N.W. Hagood, ed., Proc. SPIE 2190, SPIE—The International Society for Optical Engineering, Bellingham, Washington, pp. 495-505.

13. BOYD, J.G., and LAGOUDAS, D.C.,1994, "Microthermodynamics Analysis of the Shape Memory Effect in Composite Materials," in Proceedings of the Second International Conference on Intelligent Materials, Colonial Williamsburg PA, June 5-8, 1994, C.A. Rogers and G.G. Wallace, eds., Technomic Publishing Co., Inc., Lancaster, Pennsylvania, pp. 198-209.

14. LAGOUDAS, D.C., BO, Z., and QIDWAI, M.A., 1994, "Micromechanics of Active Metal Matrix Composites with Shape Memory Alloy Fibers," in Inelasticity and Micromechanics of Metal Matrix Composites, Studies in Applied Mechanics Vol. 41, G.Z. Voyiadjis and J-W. Ju, eds., Elsevier, Amsterdam, pp. 163-190.

15. De BLONK, B., and LAGOUDAS, D.C., 1994, "Configurations of Active Flexible Rods with Embedded Shape Memory Alloy Actuators," in Proceeding of the First International

Conference on Composite Engineering, David Hui, ed., ICCE/I-the International Community of Composites Engineering, pp. 275-276.

16. BO, Z., KURDILA, A.J., LAGOUDAS, D.C., and WEBB, G., 1995, "Identification for a Class of Nonlinear Models for Shape Memory Alloy (SMA) Embedded Elastomeric Rods," in Active Materials and Smart Structures, G.L. Anderson and D.C. Lagoudas, eds., Proc. SPIE 2427, SPIE—The International Society for Optical Engineering, Bellingham, Washington, pp. 93-106.

17. BO, Z., and LAGOUDAS, D.C., 1995, "A Unified Thermodynamic Constitutive Model and Finite Element Analysis of Active Metal Matrix Composites," in Active Materials and Smart Structures, G.L. Anderson and D.C. Lagoudas, eds., Proc. SPIE 2427, SPIE—The International Society for Optical Engineering, Bellingham, Washington, pp. 276-288.

18. BO, Z., and LAGOUDAS, D.C., 1994, "Comparison of Different Thermomechanical Models for Shape Memory Alloys," Adaptive Structures and Composite Materials: Analysis and Application, AD-Vol. 45/MD-Vol. 54, E. Garcia, H. Cudney, and A. Dasgupta, eds., American Society of Mechanical Engineers, New York, pp. 9-19.

19. BOYD, J.G., and LAGOUDAS, D.C., 1994, "A Constitutive Model for Simultaneous Transformation and Reorientation in Shape Memory Materials," Mechanics of Phase Transformations and Shape Memory Alloys, AMD-Vol. 189/PVP-Vol. 292, L.C. Brinson and B. Moran, eds., American Society of Mechanical Engineers, New York, pp. 159-177.

20. BOYD, J.G., and LAGOUDAS, D.C., 1994, "A Thermodynamical Study of the Two-Way Shape Memory Effect in Active Composites," Mechanics of Materials and Electronic Packaging: Volume 3, Coupled Field Behavior in Materials, AMD-Vol. 193, M.L. Dunn, M. Taya, and M. Saka, eds., American Society of Mechanical Engineers, New York, pp. 77-102

21. BHATTACHARYYA, A., and LAGOUDAS, D.C., 1995, "The Probabilistic Influence of Material Uncertainties on the Inelastic Response of SMA Composites," in Recent Advances in Composite Materials, S.R. White, H.T. Hahn and W.F. Jones, eds. the American Society of Mechanical Engineers, New York, pp. 237-251.

22. de BLONK, B., KURDILA, A.J., LAGOUDAS, D.C., and WEBB, G., 1995, "Identification of the Transient Response of SMA Embedded Flexible Rods", Smart Structures and Materials 1995: Smart Structures and Integrated Systems, Inderijit Chopra, ed., Proc. SPIE 2443, SPIE -The International Society for Optical Engineering, Bellingham, Washington, pp. 349-359.

23. XU, G., LAGOUDAS, D.C., WEN, J.T., and HUGHES, D., 1995, "Thermo-electro-mechanical Modeling and Structural Response of a Flexible Beam with External SMA Actuators, Smart Structures and Materials 1995: Mathematics and Control in Smart Structures, Vasundara V. Varadan, ed., Proc. SPIE 2442, SPIE -The International Society for Optical Engineering, Bellingham, Washington, pp. 503-515.

24. Bo, Z., and LAGOUDAS, D.C., 1995, "A Thermodynamic Constitutive Model for Cyclic Loading of Shape Memory Alloy Materials with Application to Two Way Training," Smart Structures and Materials 1995: Smart Materials, A. Peter Jardine, ed., Proc. SPIE 2441, SPIE - The International Society for Optical Engineering, Bellingham, Washington, pp. 118-130.

25. BHATTACHARYYA, A., and LAGOUDAS, D.C., 1995, "A Mean-Field Framework for the Characterization of SMA Polycrystals with Material Uncertainties," Innovative Processing and Characterization of Composite Materials, NCA-Vo. 201/AMD.Vol.211, Ronald F. Gibson, Tsu-Wei Chou and P.K. Raju, eds., American Society of Mechanical Engineers, New York, pp. 143-158.

26. BO, ZHONGHE and LAGOUDAS, D.C., 1996, "Phase Transformation Localization in SMA wires," Contemporary Research in the Mechanics and Mathematics of Materials, R.C. Batra and M.F> Beatty, eds., International Center for Numerical Methods in Engineering (CIMNE), Barcelona, pp. 263-274.

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SOTTOS, N.R., KLINE, G.E., QIDWAI, M.A., and LAGOUDAS, D.C., 1996, Analysis of Phase Transformation Fronts in SMA Composites," proceedings of Mathematics and Control in Smart Structures, SPIE Vol. 2715, pp. 427-438.

LAGOUDAS, D.C., BO, Z., and BHATTACHARYYA, A., 1996, "A Thermodynamic Constitutive Model for Gradual Phase Transformation of SMA Materials," proceedings of Mathematics and Control in Smart Structures, SPIE Vol. 2715, pp. 482-493.

JONNALAGADDA, J.D., SOTTOS, N.R., QIDWAI, M.R., and LAGOUDAS, D.C., 1997, "Transformation of Embedded Shape Memory Alloy Ribbons," Proceedings of the 1997 SPIE Conference, Vol. 3039, pp. 242-253 .

BO, Z., LAGOUDAS, D.C., 1997, "Modeling of Cyclic Thermomechanical Response of Polycrystalline Shape Memory Alloys," Proceedings of the 1997 IUTAM Conference on Micromechanics of Composites and Active Materials.